

Completing the Massive Star Population: Striking Into the Field

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Abstract. As a population, field massive stars are relatively enigmatic, and this review attempts to illuminate this sector of the high-mass stellar population, which comprises 20 – 25% of the massive stars in star-forming galaxies. The statistical properties of the field population are vital diagnostics of star formation theory, cluster dynamical evolution, and stellar evolution. We present evidence that field massive stars originate both *in situ* and as runaways from clusters, based on the clustering law, IMF, rotation velocities, and individual observed *in situ* candidate field stars. We compare the known properties of field and cluster massive stars from studies in the Magellanic Clouds and the Galaxy, including our RIOTS4 complete spectroscopic survey of SMC OB stars. In addition to the origin of the field massive stars, we discuss additional properties including binarity, runaway mechanisms, and some evolved spectral types.

1. Introduction: Definition and frequency of field OB stars

In the last session, we discussed massive stars within clusters, and I now turn to a more enigmatic component of the high-mass stellar population: the field stars. What is the nature of the field massive star population? In particular, are there OB stars that form *in situ* in the field, more or less isolated? Or are most massive field stars runaways that are ejected from clusters? Note that “field” stars are subject to different definitions, especially regarding the degree of isolation, both in the number of immediate companion stars and distance from massive clusters. Thus what follows is a review of studies that adopt necessarily heterogeneous definitions of the field.

For a simple definition of field OB stars, we consider the clustering law, which is the number of OB stars N_* per cluster. This is simply a manifestation of the cluster mass function, and both are known to robustly follow a -2 power-law distribution, which for the clustering law is:

$$N(N_*) dN_* \propto N_*^{-2} dN_* \quad . \quad (1)$$

If we consider only the OB stars and ignore all the lower-mass stars, then we find that this power-law extends smoothly down to $N_* = 1$, i.e., individual OB stars, which we define to be field stars (Oey et al. 2004). We obtained this result using the *UBVR* photometric survey of the entire Small Magellanic Cloud (SMC) by Massey (2002), uniformly identifying all OB star candidates from the criteria that the reddening-free parameter $Q_{UBR} \leq -0.84$ and $B \leq 15.21$. Following Battinelli (1991), we applied a friends-of-friends algorithm to assign stars to clusters, adopting the clustering length that maximizes the number of identified clusters, which is 28 pc. OB candidates having no other OB candidate within this distance are then defined to be field stars.

That these field stars are simply a smooth extension of the power-law clustering suggests that they are dominated by objects that are simply the “tip of the iceberg” on small, sparse clusters containing only the single OB stars that formed *in situ* as members of these groups. However, note that since the clustering law is presented as a logarithmic relation, we can also accommodate a significant contribution, even 50%, from runaway stars, and still present a smooth power law for the clustering law.

From this power law (equation 1), the fraction of field massive stars is (Oey et al. 2004):

$$f(\text{field}) = (\ln N_{*,\text{up}} + 0.5772)^{-1} \quad , \quad (2)$$

where $N_{*,\text{up}}$ is the number of OB stars in the richest cluster in the entire galaxy or ensemble. For most astrophysical situations, $f(\text{field})$ is in the range of about 1/3 to 1/10. For the SMC, equation 2 predicts $f(\text{field}) \sim 0.20$, while the observed value is about 0.26. This is comparable to the estimated frequency of $\sim 20\%$ for O stars in the Milky Way (Mason et al. 2009; Gies 1987).

2. The Field IMF

Given this uniformly identified sample of field OB candidates for the entire SMC, we are in the final stages of a survey to obtain spectroscopic observations for all of these stars: the Runaways and Isolated O-Type Star Spectroscopic Survey of the SMC (RI-OTS4). This is being carried out at the Magellan Baade 6.5-m telescope by multislit observations with the IMACS imaging spectrograph at a resolution of $R \sim 2600$. This yields spectroscopic classifications and radial velocities good to $10 - 15 \text{ km s}^{-1}$. Our coverage of the SMC bar region is essentially complete, while the SMC wing region is currently about 85% complete.

A primary goal of our survey is thus to provide a definitive measurement of the upper IMF in the field, which is presented at this meeting by Joel Lamb. As is well known, Massey (2002) and Massey et al. (1995) found an upper IMF power-law slope that is much steeper than the Salpeter value $\Gamma = -1.35$ in both the Large and Small Magellanic Cloud from observations of limited areas in these galaxies, obtaining $\Gamma \sim -4$. Our preliminary results confirm a steeper slope, though with a less extreme value: $\Gamma \sim -3$ (Lamb et al. 2011, these proceedings). Similarly, van den Bergh (2004) evaluated the distribution of Milky Way O stars as a function of spectral type and found a preponderance toward late types in the field relative to associations. This is thus consistent with a steeper field slope in our Galaxy as well.

Since Wolf-Rayet (WR) stars have higher-mass progenitors than typical OB stars, we can also examine the relative frequency of WR stars to probe the field and cluster IMF. In the SMC, two WR stars are in our field sample, out of a total of 12 known WR stars in this galaxy (Massey & Duffy 2001; Massey et al. 2001). This yields a field WR frequency of 17% relative to 26% for OB stars. While this difference is not statistically significant because of the tiny number of WR stars, we note that the results do suggest a lower WR frequency, as expected for a steeper field IMF.

3. Oe, Be, and B[e] Stars

Classical Oe and Be stars are another type of massive star that are easy to identify from their strong Balmer emission lines. However, the origin and frequency of this phe-

nomenon is less straightforward than for WR stars, since apparently only some fraction of OB stars go through an Oe/Be phase. Field vs cluster properties for these stars are best examined in the Magellanic Clouds, but no clear differences have been identified in the distributions of spectral type, luminosity class, and rotation velocities (Keller et al. 1999; Martayan et al. 2006, 2007). Evidence for variation in their frequency between field and clusters is also inconclusive. Our RIOTS4 survey yields a preliminary frequency of 53% and 21% for field Be and Oe stars, respectively. These high frequencies reflect the known prevalence of Oe/Be stars at low metallicity for the SMC (e.g., Maeder et al. 1999; Martayan et al. 2006).

We identified a new B[e] supergiant in the course of the RIOTS4 survey, the star LHA115-S62 (Henize 1956). Thus we have one B[e] supergiant in the field relative to the total of 6 in the SMC, adding to the five previously known B[e] supergiants (Wisniewski et al. 2007). This yields a frequency of 17% B[e] supergiants in the field, which is the same value found for WR stars.

4. Binary Stars

Statistics for binary stars are an especially important diagnostic for the origin of field stars, since theories for both star formation and dynamical ejection from clusters can make specific predictions for the frequencies and binary parameters for field stars. Because of the difficult and time-consuming nature of binary identification across the vast parameter space in binary mass ratio, separation, inclination, and period, different techniques are needed to probe the full parameter space (e.g., Sana & Evans 2011; Mason et al. 2009), ranging from high-resolution imaging with speckle interferometry to high-resolution spectroscopic monitoring. Furthermore, obtaining reliable statistics also depends on observing complete samples over appropriate time domains. Mason et al. (2009) have compiled the most complete statistics for massive star binaries to date, examining 347 Milky Way O stars in a magnitude-limited sample catalogued by Maíz-Apellániz et al. (2004). To date, they find that the field and cluster O stars have frequencies of 59% and 75%, respectively, that are at least binary or with greater multiplicity. While this difference is statistically significant, it is important to bear in mind that binary frequencies for both populations are lower limits. Sana & Evans (2011) find a cluster binary frequency around 50% for 9 Galactic OB associations; since these are typically farther than the stars in the Maíz-Apellániz et al. sample, the binary detection rate is lower. The binary frequencies for their extragalactic clusters are lower still. The frequency of binary runaway O stars is 43% (Mason et al. 2009).

Bragança et al. (2011, in preparation) obtained observations of 379 solar neighborhood B stars with the MIKE echelle spectrograph at Magellan. Preliminary results show that about 21% of these stars are double-lined spectroscopic binaries, with analysis of field vs cluster members in progress. Our RIOTS4 survey of the SMC includes binary monitoring of three fields, corresponding to about 10% of the sample. With observations of a dozen epochs in hand, about 9 out of 16 non-Be stars are single-lined spectroscopic binaries, corresponding to 60% of the sample. We caution that stochasticity is an important factor in this preliminary result.

As mentioned above, the statistics for binary stars promise to be critical diagnostics for the origin of both *in situ* and runaway field stars. At present, reliable statistics for binary orbital parameters have not yet been published, but we stress the importance of

obtaining these data. For example, we almost have useful estimates of the non-compact binary runaway frequency, which is a critical probe of dynamical ejection (§6).

5. Rotation Velocities

Rotation velocities are the parameter for which the field and cluster stars show the most revealing differentiation. It has long been known that field stars show lower values of $v \sin i$ than cluster stars (e.g., Guthrie 1984). This difference is a critical clue to the origin of field stars, and the proposed models reflect the different possible mechanisms for these origins. Wolff et al. (2007, 2008) suggest that the different rotational velocities result from the different star-formation environments, with lower turbulence in small star-forming regions resulting in lower $v \sin i$ relative to high-density, intense star-forming regions. However, Huang and collaborators suggest that the lower $v \sin i$ in the field is simply linked to a higher average age for field stars, which may be dispersed from clusters, reflecting an evolutionary spin-down effect (Huang & Gies 2008; Huang et al. 2010). They demonstrate that both field and cluster stars show an anticorrelation between $v \sin i$ and $\log g$, confirming this spin-down.

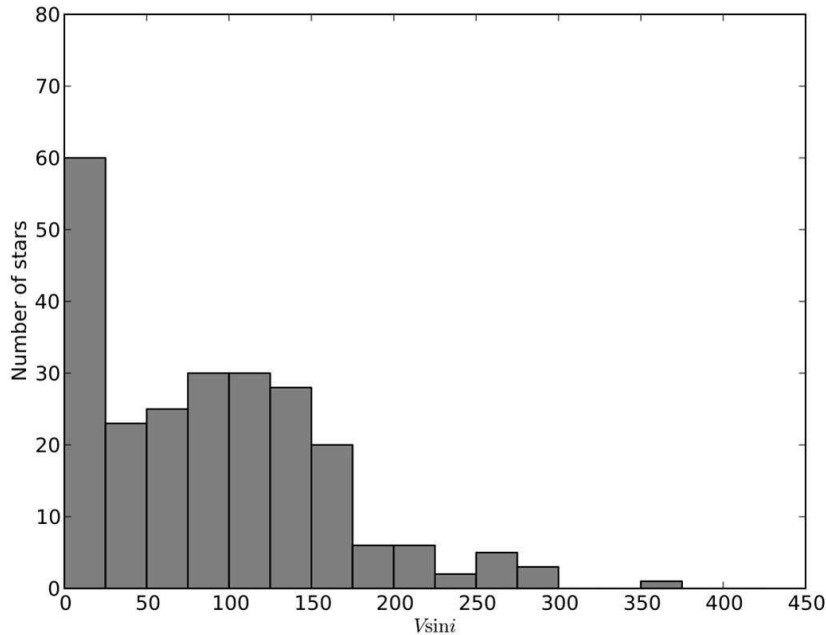


Figure 1. Preliminary distribution of $v \sin i$ for solar neighborhood B stars (Bragança et al., in preparation).

However, the field $v \sin i$ distribution strongly appears to be bimodal. We observed a large sample of solar neighborhood B stars with the MIKE echelle spectrograph at Magellan, and removed known cluster members, yielding 240 remaining stars (Bragança et al. 2011, in preparation). Interestingly, this only heightens the bimodality

apparent in the $v \sin i$ distribution (Figure 1). The bimodality is also evident in the field star sample of Abt et al. (2002), selected by Strom et al. (2005) and plotted by Wolff et al. (2007). There are also hundreds of stars in this sample, so the double-peak form of the $v \sin i$ distribution is statistically significant, and similar to that in Figure 1. Garmany et al. (2010) also identified a bimodal distribution in their sample of 150 Milky Way outer disk B stars, which were also observed with MIKE at Magellan. In all cases, we see a component of slow rotators which peak below $v \sin i \sim 25 \text{ km s}^{-1}$, and fast rotators with a much broader $v \sin i$ component peaking near 100 km s^{-1} . Meanwhile, a sample of high-latitude, field main-sequence B stars studied by Martin (2006) does *not* show the bimodal distribution and apparently shows only the broad component of fast rotators. Martin argues that since these stars are outside the Galactic plane, they must be strongly dominated by runaway stars. Therefore, we suggest that *the fast rotators seen in the bimodal distributions are runaway stars, while the population of slow rotators are field stars that formed in situ*. This is consistent with the model of Wolff et al. (2007) that $v \sin i$ correlates with star formation density. Therefore, this may be strong evidence that massive stars do form *in situ* in the field.

6. Runaway Stars

Runaway stars ejected from clusters are commonly observed and understood to be a significant component of the field massive star population. O stars show a higher frequency, around 10 – 30% runaways, relative to B stars, around 5 – 10% runaways (Moffat 1998; Gies 1987). This mass dependence is an important clue to the origin of runaway stars, for which there are two general models. The first is dynamical ejection from 3- and 4-body interactions, with the latter taking place as binary-binary interactions, in which the ejected stars may or may not be separated. There has been substantial work done in simulating these dynamical interactions, pioneered by, e.g., Poveda et al. (1967), Mikkola (1983), and Leonard & Duncan (1988, 1990). The second mechanism to generate runaway stars is via supernova ejection, in which a binary companion explodes and releases the surviving star as a runaway (e.g., Zwicky 1957; Blaauw 1961).

It is difficult to determine which of these mechanisms dominates, but that result would itself be a vital diagnostic for cluster dynamical evolution, binary fractions, and star formation. The strongest test is the frequency of runaway, double-lined spectroscopic binaries (SB2) or visual binaries, which *must* be generated by the dynamical ejection scenario. Note that single-lined spectroscopic binaries may have a compact secondary, which could be generated by the supernova ejection model. Out of 42 runaways in the Galactic field O star sample, Mason et al. (2009) identify 3 as SB2 and 11 showing visual multiplicity. The two categories are not mutually exclusive, and the visual multiples may include line-of-sight interlopers. Thus, the frequency of non-compact, multiple runaways may be around 10 – 20% of O star runaways. If this relatively high value is confirmed, it demonstrates the significance of the dynamical ejection mechanism. This may even dominate the massive runaway population, since this process also contributes many single runaway stars.

Blaauw (1993) suggested that stars ejected by the supernova binary mechanism should be He-enriched from contamination by the explosion event. Such an enhancement indeed has been observed by Blaauw and by Hoogerwerf et al. (2001) in a sample of local runaway stars at distances within 700 pc. Another diagnostic, proposed by Martin (2006), is that the runaway star's $v \sin i$ should correlate with its space velocity,

since the star’s runaway velocity should be closely linked to its former binary orbital velocity. To produce a high, runaway velocity, the orbital velocity also must have been high, implying a tight binary that was most likely orbitally locked with the companion, and hence the ejection and orbital velocities should be similar. However, Martin’s (2006) sample of high-latitude field B stars does not show such a correlation, suggesting that the supernova ejection mechanism may not be important for that population. While Martin (2006) comes to the opposite conclusion from Hoogerwerf et al. (2001), he notes that the two studies are based on very different samples, with the latter perhaps representing a younger runaway population, owing to the stars’ proximity within the Galactic disk. Further studies can examine the age-dependence of runaway frequencies and properties by targeting evolved stars (e.g., Berger & Gies 2001; Slettebak et al. 1997). Our understanding is still extremely uncertain, but the modest existing evidence described above perhaps slightly favors dynamical ejection over supernova ejection as the dominant mechanism for producing massive runaway stars.

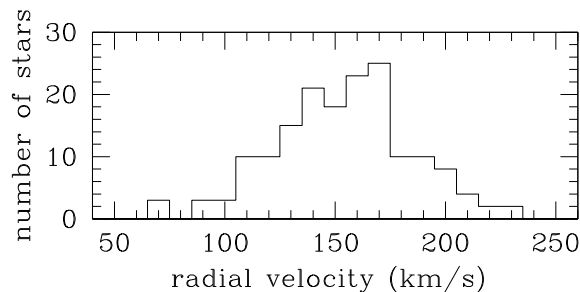


Figure 2. Preliminary distribution of RIOTS4 radial velocities for SMC field OB stars.

Much more study is needed, especially observations to better quantify the properties of runaway stars. With our RIOTS4 survey, we are able to measure radial velocities of our complete OB star sample with typical accuracy of $10 - 15 \text{ km s}^{-1}$. Our preliminary distribution (Figure 2) has a FWHM $\sim 60 \text{ km s}^{-1}$, which includes large-scale SMC motions. In particular, the SMC Wing region is offset from the SMC Bar by about 30 km s^{-1} . From the fairly smooth velocity distribution, it is therefore difficult to infer the existence of any significant features that may originate from different runaway mechanisms, but quantitative predictions are needed to fully exploit this complete data set. Our results are qualitatively similar to the distributions presented by Evans & Howarth (2008), who compiled the radial velocities for samples of OB stars that include both cluster and field stars. Our sample is smaller than theirs, but with much stronger selection criteria and spectral resolution that is almost double theirs.

7. In-Situ Field Stars

The existence of massive field stars that formed *in situ* may depend on the exact definition of field stars (§1). While candidates for such stars do exist (e.g., Selier et al., these proceedings), it remains to be determined whether any of these form in true isolation. But in any case, the sparsest regime sets strong constraints on the physics of star formation. For example, it is much more difficult to generate isolated massive stars with competitive accretion models (e.g., Bonnell et al. 2004) than with core collapse models (e.g., Krumholz & McKee 2008).

There do appear to be examples of massive stars in sparse groups containing only a few other low-mass stars. Such groups might be remnants of rapidly-dissolved clusters, but it remains likely that these are examples of extreme, low-density star formation. de Wit et al. (2004, 2005) find that locally, about 12% of Galactic O stars are in such sparse groups. Using *HST*/ACS observations, we found three SMC field O stars to be within sparse, low-mass groups, out of six apparently-isolated field O stars (Lamb et al. 2010). We carried out Monte Carlo simulations based on the -2 power law clustering (equation 1) and a Kroupa (2001) IMF, assuming these two relations to be completely independent; in particular, we assumed no dependence of the stellar upper-mass limit on cluster mass. The observed sparse O star groups fall easily within the allowed parameter space of these simulations when examining the mass ratio of the two highest-mass stars and the maximum-mass star m_{max} per cluster. However, these sparse O star groups are inconsistent with the proposed relation between m_{max} and cluster mass, suggesting that in general, the integrated galaxy IMF (IGIMF) should not be steeper than the IMF in individual clusters.

8. Conclusion: In-Situ Field Stars In-Situ and Runaways

The evidence presented above supports the existence of both runaways and an *in-situ* component contributing significantly to the field massive star population. We commonly observe runaway stars and we know that they exist; thus, the main question is whether field massive stars also form *in situ*. I suggest that several lines of evidence support their existence. First, there are many instances of observed high-mass stars that are in sparse, low-mass groups, or even candidate *in situ* isolated stars. Second, the bimodal $v \sin i$ distribution strongly suggests that the slow rotators are *in situ* field OB stars. Third, the upper IMF in the field appears to be significantly steeper than measured in clusters; whereas, if the field consists purely of runaways, then its upper IMF should be flatter than in clusters, since O stars have a higher runaway frequency than B stars. And fourth, there is no discontinuity between the field stars and clusters in the cluster mass function (equation 1).

The runaways originate from either dynamical ejection or supernova ejection, and presently, the evidence does not strongly favor one scenario over the other. There may be slightly stronger support for dynamical ejection, since we do see a non-negligible frequency of double-lined spectroscopic binaries and visual binaries, both of which can only originate by dynamical ejection. The lack of correlation thus far, between rotation and space velocity also suggests that supernova ejection is not a dominant process. However, observed He abundance enhancements in runaway stars do support the supernova ejection model. All these results are based on limited, individual studies and far more work is needed to establish the trends, and better probe diagnostics of the ejection mechanisms.

Our understanding of the field massive star population is gradually emerging, but much more study is needed to fully illuminate this enigmatic, but substantial, population. An especially critical area is the binary population: some of the most powerful diagnostics will be revealed by statistics of the binary orbital parameters. These are difficult and time-consuming to obtain, but they will be powerful diagnostics of runaway ejection mechanisms, constrain star formation and IMF theories, and cluster evolution, as well as the nature of the field population. Binary population synthesis models and N-

body dynamical simulations are already mature areas of study, and more observations in particular are needed to test the models.

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